Appendix 4

4.1. Total Vertical Time of Travel

Total vertical time of travel is defined as the time required for secondary treated wastewater to migrate upward from the point of injection to the USDW and hypothetical receptor wells. Given the velocity and distance of travel, the time it takes to travel the distance can be determined by dividing the distance by the velocity. To estimate the vertical travel time (t) through each hydrologic unit, the thickness of the unit (b) is divided by the seepage velocity (v_s) (Eqn. 3). Seepage velocity is defined as the velocity representing the average rate at which ground water moves (Fetter, 1994) and is estimated by dividing the Darcy flow (q) by the porosity (n) of the hydrologic unit (Eqn. 4). Porosity represents the ratio between the volume of voids over the total volume of the media (Freeze and Cherry, 1979). In this analysis, published porosity values were used. Darcy flow is defined as fluid flow through porous media (e.g. sand) (Freeze and Cherry; 1979), taking into consideration that ground water flows through porous media, Darcian assumptions must be applied. Darcy flow takes into account vertical hydraulic conductivity (K) and the hydraulic gradient (I) (Eqn. 5). Hydraulic conductivity represents the ability of the media to transmit water (Fetter, 1994). Hydraulic gradient is estimated by dividing the total pressure head (H_T) by the thickness of the hydrologic unit (Eqn. 6).

$$t = \frac{b}{v_s} \qquad \text{(Eqn. 3)}$$

$$v_s = \frac{q}{n} \qquad \text{(Eqn. 4)}$$

$$q = K \times I \qquad \text{(Eqn. 5)}$$

$$I = \frac{H_T}{b} \qquad \text{(Eqn. 6)}$$

4.2. Total Pressure Head

Pressure head can be simply viewed as a driving force for vertical migration of treated wastewater. In this analysis, two driving components of pressure head were considered. Pressure head due to injection (H_I) and pressure head due to buoyancy (H_B). These components are described separately below. The total pressure head acting on the overlying hydrogeologic unit may be expressed as the sum of the buoyancy and the injection components (Eqn. 7):

$$H_T = H_I + H_B \qquad \text{(Eqn. 7)}$$

4.2.1. Pressure Head Due to Injection

Injection-derived pressure is a controlling force that drives the wastewater plume throughout the regional ground water system. As millions of gallons of water are injected into the aquifer, that volume displaces an equivalent volume of native water in the formation. This causes a pressure build-up in the aquifer, which must be dissipated throughout the aquifer unit.

The vertical migration component due to injection-derived over-pressuring was calculated using the following leaky aquifer steady-state pressure drawdown/increase equation (Gupta, 1995).

$$H_I = \frac{Q}{2\pi T} K_O\left(\frac{r}{B}\right) \qquad \text{(Eqn. 8)}$$

$$H_I = \frac{Q}{2\pi T} \ln\left(1.123\frac{B}{r}\right) \text{ for } \frac{r}{B} < 0.05 \qquad \text{(Eqn. 9)}$$

where:

- Q = Injection rate
- K = Vertical hydraulic conductivity
- b = Thickness of aquifer
- T = Transmissivity of the receiving unit = $K \times b$ (Eqn.10)
- r = Distance from injection well
- $K_O\left(\frac{r}{B}\right)$ = Zero-order modified Bessel function of the second kind (Tabulated values)
- B = Leakage factor = $\sqrt{\frac{T}{K'/b'}}$ (Eqn. 11)
- K' = Vertical hydraulic conductivity of the overlying layer
- b' = Thickness of the overlying layer

A distance of one hundred feet from the injection well (r) was chosen in Pinellas County, where pressure due to injection occurs. A distance of one hundred feet was chosen because at this distance away from the injection point, it is assumed that steady upward flow would be occurring. This value will also result in a conservative travel time estimation. The closer one is to the injection point, the greater the effects of pressure due to injection, resulting in a faster travel time. Representative injection rates of 112.5 million gallons per day (mgd) in Dade County, 7 mgd in Pinellas County, and 5 mgd in Brevard County were used (Starr et al., 2001, Florida Department of Environmental Protection, 2001 and Florida Department of Regulation, 1989). In Dade and Brevard Counties the pressure head due to injection is negligible due to injection into the Boulder Zone. The Boulder Zone is highly karstified with cavernous pores and wide fractures, which does not constrain the flow of injected effluent; therefore negligible pressure build up will occur (Singh et al., 1983; Haberfeld, 1991).

4.4.2. Pressure Head Due to Buoyancy

The buoyancy pressure head component, related to variations in fluid temperature and fluid density, also influences upward migration of the injectate. The wastewater injected into the aquifer is relatively fresh in comparison to the native ground water found in the injection zone (Florida Department of Environmental Protection, 1999a). As a result, the less dense injected wastewater rises above the denser, native ground water. In hydraulic terms, the fresh water is more buoyant than the salt water.

Density is also dependent on temperature: warm water is less dense than cold water. The temperature difference between the warm injected wastewater and the comparatively cold, native formation water is yet another driving force for the upward migration of the plume.

Upward pressure heads due to the buoyancy (from salinity and temperature differences) were calculated using the following derived equation (Hwang and Hita, 1987):

$$H_B = \frac{[\rho_n h - \rho_i h]}{\rho_{water}} \qquad \text{(Eqn. 12)}$$

where: H_B = Pressure head due to buoyancy (salinity and temperature gradient)
ρ = Density of native (n) and injected (i) fluid
h = Height of injected fluid (through each hydrologic unit)

Steady state conditions were assumed in this analysis. Under steady state conditions, no mixing or dispersion occurs and the injectate has a continuous path to the hypothetical water supply well or USDW. Travel times were estimated through each hydrologic unit. Therefore a simplifying assumption, valid for steady state conditions, was that the height of the injected fluid is the thickness of the hydrologic unit.

There is a natural salinity and temperature gradient in the native fluid. The native fluid in the injection zone has salinity comparable to sea water and becomes comparable to fresh water at the surficial aquifer. The injected wastewater has salinity comparable to fresh water therefore the pressure head due to buoyancy (salinity gradient) will decrease as the injectate moves closer to the hypothetical water supply well. The same result will occur with respect to temperature gradient. The temperature of the native fluid in the injection zone is approximately 60 degrees Fahrenheit and can reach up to 80 degrees in the surficial aquifer. The injected wastewater has a temperature of 80 degrees. As the injected wastewater moves closer to the hypothetical water supply well, the pressure head due to buoyancy (temperature gradient) will decrease. The buoyancy calculations were based on the discretization of the density gradient due to temperature and salinity difference.

In this analysis, two scenarios were considered: 1) porous media flow and 2) bulk flow through preferential flow paths. To assess the two scenarios, primary porosities and hydraulic conductivities and secondary porosities and hydraulic conductivities were used in the above equations, respectively. The results are presented in the following tables for Dade, Pinellas and Brevard Counties.

Appendix Table 4-1 Vertical Travel Time to Receptor Well

(Scenario 1: Porous Media Flow)

Dade

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Biscayne Aquifer	230	100	15	0.31	130	2550	1	0	0.66	0.004	0.058	0.188	1.9	Years
Intermediate Confining Unit	840	230	0.10	0.31	610	61	5	0	4.69	0.008	0.001	0.002	674	Years
Upper Floridan Aquifer	2060	840	0.42	0.32	1220	512	19	0	18.5	0.015	0.006	0.020	168	Years
Middle Confining Unit	2550	2060	0.04	0.43	490	20	23	0	22.5	0.046	0.002	0.004	314	Years
Lower Floridan	2750	2550	0.10	0.40	200	20	15	0	14.6	0.073	0.007	0.018	30	Years
Boulder Zone	3000	2750	65	0.20	250	16250	12	0	12.0	0.048	3.13	15.7	16	Days
												Travel Time	**1,188**	**Years**

Pinellas

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Surficial Aquifer	56	30	7	0.31	26	182	0.1	0	0.10	0.004	0.027	0.087	297	Days
Intermediate Confining Unit	275	56	1.2	0.31	219	263	1.8	0	1.82	0.008	0.010	0.032	18.6	Years
Upper Floridan Aquifer	1250	275	0.3	0.226	975	293	15.6	533	548	0.563	0.169	0.747	3.58	Years
												Travel Time	**23**	**Years**

Brevard

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Surficial Aquifer	130	100	13	0.31	30	390	0	0	0.125	0.004	0.054	0.175	172	Days
Intermediate Confining Unit	340	130	0.10	0.31	210	21	2	0	1.56	0.007	0.001	0.002	240	Years
Upper Floridan Aquifer	665	340	0.20	0.26	325	65	6	0	6.13	0.019	0.004	0.015	61	Years
Middle Confining Unit	1000	665	0.04	0.43	335	13	11	0	11.0	0.033	0.001	0.003	301	Years
Lower Floridan	2460	1000	0.10	0.40	1460	146	45	0	45.4	0.031	0.003	0.008	515	Years
Boulder Zone	2754	2460	65	0.20	294	19110	47	0	46.9	0.160	10.4	51.9	5.67	Days
												Travel Time	**1118**	**Years**

Appendix Table 4-2 Vertical Travel Time to USDW

(Scenario 1: Porous Media Flow)

Dade

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Upper Floridan Aquifer	2060	1500	0.42	0.32	560	512.4	18.5	0	18.5	0.015	0.006	0.020	77	Years
Middle Confining Unit	2550	2060	0.04	0.43	490	19.6	22.5	0	22.5	0.046	0.002	0.004	314	Years
Lower Floridan	2750	2550	0.1	0.4	200	20	14.6	0	14.6	0.073	0.007	0.018	30	Years
Boulder Zone	3000	2750	65	0.2	250	16250	12.0	0	12.0	0.048	3.13	15.7	16	Days
												Travel Time	**421**	**Years**

Pinellas

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Upper Floridan Aquifer	1250	680	0.30	0.226	570	293	16	533	548	0.56	0.17	0.75	2	Years
												Travel Time	**2**	**Years**

Brevard

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Lower Floridan	2470	1500	0.1	0.4	970	146	45	0	45	0.03	0.00	0.01	342	Years
Boulder Zone	2754	2470	65.00	0.20	284	19110	47	0	47	0.160	10.378	51.892	5	Days
												Travel Time	**342**	**Years**

Appendix Table 4-3 Vertical Travel Time to Receptor Well

(Scenario 2: Preferential Flow Paths)

Dade

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Biscayne Aquifer	230	100	15	0.31	130	2550	1	0	0.7	0.004	0.058	0.19	1.9	Years
Intermediate Confining Unit	840	230	2.38	0.10	610	61	5	0	4.7	0.008	0.018	0.18	9.1	Years
Upper Floridan Aquifer	2060	840	2.38	0.10	1220	512	19	0	18.5	0.015	0.036	0.36	9.3	Years
Middle Confining Unit	2550	2060	1.5	0.10	490	20	23	0	22.5	0.046	0.069	0.69	1.9	Years
Lower Floridan	2750	2550	0.1	0.10	200	20	15	0	14.6	0.073	0.007	0.07	7.5	Years
Boulder Zone	3000	2750	65	0.2	250	16250	12	0	12.0	0.048	3.131	15.66	16	Days
												Travel Time	**30**	**Years**

Pinellas

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Surficial Aquifer	56	30	7	0.31	26	182	0.1	0.0	0.1	0.003873	0.027	0.09	297	Days
Intermediate Confining Unit	275	56	1.50	0.10	219	329	1.8	0.0	1.8	0.008313	0.012	0.12	5	Years
Upper Floridan Aquifer	1250	275	2.38	0.10	975	2321	16	122	138	0.141048	0.336	3.36	290	Days
												Travel Time	**6.4**	**Years**

Brevard

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Surficial Aquifer	130	100	13	0.31	30	390	1	0	1	0.03	0.39	1.26	24	Days
Intermediate Confining Unit	340	130	2.38	0.10	210	499.8	6	0	6	0.03	0.071	0.714	294	Days
Upper Floridan Aquifer	665	340	2.38	0.10	325	773.5	11	0	11	0.03	0.080	0.799	1	Years
Middle Confining Unit	1000	665	1.50	0.10	335	502.5	16	0	16	0.05	0.069	0.695	1	Years
Lower Floridan	2460	1000	0.10	0.10	1460	146	45	0	45	0.03	0.003	0.031	129	Years
Boulder Zone	2754	2460	65	0.20	294	19110	47	0	47	0.16	10.38	51.89	6	Days
												Travel Time	**136**	**Years**

Appendix Table 4-4 Vertical Travel Time to USDW

(Scenario 2: Preferential Flow Paths)

Dade

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Upper Floridan Aquifer	2060	1500	2.38	0.10	560	512.4	19	0	19	0.015	0.036	0.36	4	Years
Middle Confining Unit	2550	2060	1.50	0.10	490	19.6	23	0	23	0.046	0.069	0.69	2	Years
Lower Floridan	2750	2550	0.1	0.1	200	20	15	0	15	0.073	0.007	0.07	8	Years
Boulder Zone	3000	2750	65	0.2	250	16250	12	0	12	0.048	3.1	15.7	16	Days
												Travel Time	**14**	**Years**

Pinellas

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Upper Floridan Aquifer	1250	680	2.38	0.1	570	2321	16	122	138	0.14	0.34	3.36	170	Days
												Travel Time	**170**	**Days**

Brevard

Hydrogeologic Units	Injection Fluid Travel (bls)		Vertical Hydraulic Conductivity (K_V)	Porosity (n)	Aquifer Thickness (effective) (b)	Transmissivity (T)	H_B	H_I	H_T	Hydraulic Gradient (I)	Darcy Velocity (q)	Seepage Velocity (v_s)	Travel Time (t)	
	From (feet)	To (feet)	(ft/day)		(feet)	(ft^2/day)	(feet)	(feet)	(feet)		(ft/day)	(ft/day)		
Lower Floridan	2470	1500	0.1	0.1	970	146	45	0	45	0.031	0.003	0.031	86	Years
Boulder Zone	2754	2470	65.00	0.20	284	19110	47	0	47	0.160	10.4	51.9	5	Days
												Travel Time	**86**	**Years**